Memory enhancement in colloidal suspensions

Multiple transient memories in experiments on sheared non-Brownian suspensions
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Recommended with a commentary by A. Alan Middleton, Syracuse University

Many people claim that background music or conversation helps them study for an exam. Paulsen, Keim, and Nagel present experimental support for this claim, if you are willing to make the leap that the person studying can be modeled as a nonequilibrium suspension of colloids subject to shear in a Couette geometry. The authors find that drift or noise enables a colloidal system to store multiple memories. Without noise, only a single memory is stored. Though any putative connection with reviewing for an exam needs much more work, this elegant experiment is well worth considering, as it enriches our view of memory or hysteresis in complex matter.

Many condensed matter systems exhibit intricate memory behaviors. In the simplest forms of memory, the history of global externally imposed parameters, such as temperature, magnetic field, or stress, are somehow encoded in the material. There is significant variety in the features of such global memory or hysteresis. Hysteresis in scalar random field ferromagnets, as modeled by the mean field model of Preisach and the finite dimensional models with transitions studied by Sethna, Dahmen, and collaborators [Sethna et al., 1993], is a classic example of memory. The functional that relates the magnetization to the magnetic field history has known mathematical structure (assuming slow but non-equilibrium variation). This structure explains features such as return point memory that leads to closed hysteresis loops. Hysteresis in random exchange magnets or mesoscopic spin ice is more complicated even in zero temperature simulations in external fields, as the assumptions that can lead to return point memory no longer hold [Pierce et al., 2005, Deutsch and Narayan, 2003, Katzgraber and Zimanyi, 2006]. Experiments on spin glasses at finite temperature show rich aging, rejuvenation, and memory effects where samples can recapitulate their cooling protocol in great detail when warmed [Dupuis et al., 2005]. Simpler memory effects are seen in polymeric materials. Charge density wave materials seem to have memories most closely related to those in sheared colloidal suspensions. Electrically driven charge density wave materials can "remember" the lengths of previously applied pulses [Coppersmith et al., 1997] in a transient manner, as will be reviewed below for suspensions. In general, a major challenge is to classify the types of memory exhibited and to explain the dependence of any universality class on the microscopic physics.

Sheared colloidal suspensions exhibit intriguing behaviors. Past experiments have carefully explored the transition between microscopically reversible and irreversible dynamics as the amplitude of shearing is increased [Pine et al., 2005, Corte et al., 2008]. The reversible regime is not wholly elastic, as plastic arrangements can be microscopically cyclic [Keim and Arratia, 2013]. Simulations of 2D colloidal models and 3D sheared amorphous solids have been used to explore how single cycles of parameters are robustly stored and how nested cycles at multiple shear amplitudes can be stored. But multiple memories are seen in simulation only in the presence of noise or by driving the system into the irreversible regime [Keim et al., 2013, Fiocco et al., 2014].

It is this claim that multiple memories require noise that has now been verified and explored in experiments [Paulsen et al., 2014]. Paulsen and collaborators cyclically shear colloidal suspensions with dye in the fluid illuminated by a laser sheet. The colloidal particles are density and index matched with the fluid, the shear rate gives a very low Reynolds number and a high Peclet number (low inertia, high viscosity; low diffusion, high advection). For small shear cycles of constant amplitude, the particle motion converges to a cyclic pattern, thereby "remembering" the maximum shear amplitude. This memory is evidenced by the singular response seen when shear amplitudes are increased just past the training amplitude. This singular memory fades on the time scales of tens of seconds, however, probably due to various drifts in the particle positions. If a more complex sequence is used, interleaving larger and smaller shear cycles, the suspension *initially* remembers both amplitudes. However, after many training sequences, only the singular response at the larger amplitude shear forcing singularity remains. As seen in simulations, the larger amplitude attractor eventually incorporates the smaller amplitude cycle, so that the singular response for the smaller cycles fades when they are interleaved with larger cycles. The central result of this experiment comes from introducing a time delay between training sequences: if the interleaved shear cycles of varying amplitude are separated by time delays, the memory of the smaller amplitude cycles reappears and a singularity in the shear response at both amplitudes is observed at long times.

The exact mechanism of this noise or drift assisted memory could be explained in several ways. One statement might be that the noise allows the smaller amplitude cycle to be reinforced during training. Another is that the large amplitude shear cycle is dislodged by drifts, allowing for the smaller amplitude cycle to be reinforced. The complete explanation probably requires integrating these and more complex views.

Regardless of the exact explanation for the results, this experiment compels us to explore the subject further. Building a classification of global memories will depend on building a general characterization of the attractors in high dimensional spaces under cyclic variation of parameters, the speed of equilibration to these attractors, how these attractors are related for different forcing ranges, and how these attractors are affected by drift and noise. Extensions of the protocols to various lengths of pauses between different parts of the training cycle might help explain more clearly how drift dislodges the dominant cycles. Cycles that are not nested, but instead overlapping, might also be studied.

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